GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT INITIATION

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Date: May 7, 1976

Project Title: Nuclear and X-Ray Spectroscopy with Radioactive Sources

Project No: G-33-611 (Continuation of G-33-688)

Project Director: Dr. R. W. Fink

Sponsor: Energy Research & Development Admin., Oak Ridge Operations, Oak Ridge, Tenn. 37830

Agreement Period: From February 1, 1976 Until January 11, 1977

Type Agreement: Contract No. AT-(40-1)-3346, Modification No. 12

Amount:
$70,500 ERDA Funds (G-33-611)
90,208 GIT Contribution (G-33-369)
$160,708 TOTAL Estimated Cost

Reports Required: Publication Preprints; Publication Reprints; Annual Progress Report; Final Report.

Sponsor Contact Person (s):

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Contractual Matters
(thru OCA)

Defense Priority Rating: NONE

Assigned to: School of Chemistry (School/Laboratory)

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SPONSORED PROJECT TERMINATION

Date: April 28, 1977

Project Title: Nuclear & X-Ray Spectroscopy with Radioactive Sources

No Action by us - adz

Project No: G-33-611 (continued by G-33-622)

Project Director: Dr. R. W. Fink

Sponsor: Energy Research and Development Administration

Effective Termination Date: 1/31/77 (end of Mod. 12 period)

Clearance of Accounting Charges: by 1/31/77

Grant/Contract Closeout Actions Remaining:

- _ Final Invoice and Closing Documents
- _ Final Fiscal Report
- _ Final Report of Inventions
- _ Govt. Property Inventory & Related Certificate
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Report ~~Inventory~~ submitted 11 Mar 77

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ORO–3346–196

NUCLEAR SPECTROSCOPY WITH RADIOACTIVE SOURCES

Twelfth Annual Progress Report
U.S. Energy Research and Development Administration
AT (40–1)–3346

R.W. Fink
Professor of Chemistry & Senior Investigator

October 31, 1976

1976

School of Chemistry
GEORGIA INSTITUTE OF TECHNOLOGY
Atlanta, Georgia 30332

ORO-3346-196

NUCLEAR AND X-RAY SPECTROSCOPY WITH RADIOACTIVE SOURCES

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TABLE OF CONTENTS

1.0 INTRODUCTORY OVERVIEW

Considerable effort has been devoted this year to the development of a number of simple concepts of nuclear structure that have emerged from our earlier UNISOR* experiments and from the nuclear systematics program that we have been pursuing for four years. The most notable result of these efforts is the evidence we have accumulated in support of a residual quadrupole pairing force. A number of decay scheme studies, using exclusively on-campus facilities, are in progress to test the new structural concepts that have come out of our UNISOR work. These concepts are:

i) Particle-core coupling and the role played by an effective core to which the odd nucleon couples;

ii) The triaxial rotor model and the ability of its formulation (following Meyer ter Vehn) to provide a unified description of transitions from weak to strong coupling, deformation-aligned to rotation-aligned coupling, spherical to deformed shapes, and prolate-deformed to oblate-deformed shapes for single-particle motion in odd-mass nuclei;

iii) The shell model and the occurrence of intruder states; ie, states that intrude across closed shells to appear near the Fermi energy of spherical nuclei lying adjacent to and on the other side of the shell closure; and

iv) The residual pairing force and the separate contributions of oblate and prolate (up-sloping and down-sloping) Nilsson orbitals to the pairing correlations, due to a quadrupole as well as the familiar monopole components of the pairing force.

Our evidence that a residual quadrupole pairing force plays a widespread role in determining the properties of the states of the nucleus is a completely new development. This force promises to give a much better understanding of excited

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*UNISOR is a consortium of 14 institutions and is supported by them and by ERDA. The member institutions are: Univ. of Alabama in Birmingham, Georgia Institute of Technology, Emory University, Furman University, Univ. of Kentucky, Louisiana State University, Univ. of Massachusetts, Univ. of South Carolina, Univ. of Tennessee, Tennessee Technological University, Vanderbilt University, Virginia Polytechnic Institute and State University, Oak Ridge Associated Universities, and Oak Ridge National Laboratory.

0+ states in doubly-even nuclei, provides a very complete framework for the model description of non-closed shell nuclei, and appears to play an important role in the determination of the heights of fission barriers.

This year we have organized our progress report on nuclear spectroscopy research in terms of these four concepts, rather than by listing experimental projects individually; however, all experimental measurements are included explicitly in the details following below.

We have fully developed and streamlined our on-campus handling of UNISOR data through the writing of a variety of tape-reading routines and through the acquisition of an interactive CRT computer terminal located in our laboratory and coupled to the Georgia Tech CDC-Cyber-70 main computer. These data handling facilities now enable us to shorten the time spent in Oak Ridge for the experimental runs and to handle most of the UNISOR work on the campus.

Our ability to acquire and analyze nuclear lifetime data has been broadly developed both for UNISOR experiments and for on-campus measurements. A digital clock for multiple time analysis has been built at Georgia Tech for use at UNISOR for our program of nuclear lifetime measurements in the range 10 μsec to 1 sec. We are currently assembling and testing equipment to measure nuclear lifetimes in the range of 0.1 to 10 nanosec.

The main thrust of our UNISOR experiments has been the extension of our systematic studies in the odd-mass Ir, Pt, Au, Hg, and Tl isotopes, A = 183 - 197, in order to test and refine the structural concepts that we are developing. This UNISOR work has involved Dr. J. L. Wood, Dr. M. S. Rapaport, Dr. R. A. Braga, and Dr. R. W. Fink of the School of Chemistry and Dr. D. A. McClure of the School of Physics. We have two graduate students conducting PhD thesis work at UNISOR: Mr. G. M. Gowdy (Chemistry), who has been on ORAU fellowship at Oak Ridge, and Mr. M. Grimm (Physics), who has been awarded an ORAU fellowship beginning September, 1976. Much of the running time has been assigned to completing the studies of levels in the odd-mass Tl isotopes and to characterizing the decays of very neutron-deficient species around ^{185}Hg, produced from a highly enriched (93%) ^{180}W target with 1 - 2 μA beams of 150 - 180 MeV $^{14}N^{+5}$ ions from ORIC. Target/ion source development at UNISOR is steadily progressing, particularly in the case of surface ionization designs. Experience over the past year (with the Pb isotopes) has shown that chemical effects in the ion source are far more pronounced than was originally anticipated and suggests that the use of the CCl_4 technique will be predominantly on a trial and error basis.

An invited paper summarizing overall UNISOR research was presented by Dr. J. L. Wood at the 3rd International Conference on Nuclei Far from Stability held in Cargese, Corsica, France, May 19 - 26, 1976.

A number of decay scheme studies are in progress using reactor-produced activities. These have involved Mr. W. S. Lewis, Mr. A. I. Saleh, and Mr. C. Papanicolopulos and are mostly aimed at answering questions in neutron-rich nuclei arising from our program of nuclear systematics. Details of these studies are given below.

2.0 NUCLEAR SPECTROSCOPY

2.1 Nuclear Systematics and Models

This work entails the compilation and evaluation of nuclear data both from UNISOR experiments and from the published literature. The data are organized into tables and classified and graphed. Systematic trends of excited states are followed to identify specific coupling schemes and simple modes of excitation, and these are interpreted, where possible, by fitting to current models.

This year our studies have concentrated on odd-mass nuclei and the systematics of the coupling of an odd nucleon to the core. Results of UNISOR research in the transition region $77 \leq Z \leq 81$, $104 \leq N \leq 116$ continue to be a strong influence on these studies. We have formulated our odd-mass systematics studies into a number of simple concepts: namely, particle-core coupling and the definition of an effective core to which the odd nucleon couples; the tri-axial rotor model; the shell model and intruder states; and the use of a quadrupole as well as a monopole component to the pairing force. These concepts emphasize the role of an unpaired nucleon as an effective probe of core shapes and pairing degrees of freedom in the core. A clearer picture is emerging for shape coexistence, triaxial shapes, low-lying 0+ states, and backbending in doubly-even nuclei, as a result of these odd-mass systematics studies. It is these topics which are central to improving our understanding of the yrast and low-energy structure of doubly-even nuclei, the systematic study of which is currently suspended until the above concepts are fully developed. Further details of these concepts are given below. (J. L. Wood)

2.1.1 Particle-core Coupling and Effective Cores

Our main goal in the exploration of particle-core coupling has been the definition of the effective core itself. We have had remarkable success in the odd-mass Ir, Au, and Tl isotopes by using neighboring doubly-even isotopes of Pt, Hg, and Pb as cores for the $h_{11/2}$ holes in Ir, Au, and Tl, respectively; and Pt and Hg as cores for the $h_{9/2}$ particle in Au and Tl, respectively. This has been most dramatically demonstrated in ^{189}Au, as mentioned in last year's Annual Report and in a recent publication[1]. The $h_{11/2}$ and $h_{9/2}$ orbitals are believed to be

[1] J. L. Wood, R. W. Fink, E. F. Zganjar, and J. Meyer ter Vehn, Phys. Rev. C14, 682 (1976).

relatively pure hole and particle states and thus can be described by coupling a single-j nucleon to the core. Such a model has found a highly simple treatment in the particle(hole)-rotor coupling model[2] and its extension to triaxial shapes (see ref. 3 and text below).

[2] F. S. Stephens, Rev. Modern Phys. 47, 43 (1975).

[3] J. Meyer ter Vehn, Nuclear Phys. A249, 111, 141 (1975).

The coupling to the core of both the $h_{11/2}$ holes and the low-spin positive-parity quasiparticle states in the odd-mass Au isotopes is extraordinarily stable[4]. The $h_{11/2}$ hole coupling can be understood in terms of the corresponding stability of the neighboring doubly-even Hg cores. However, the low-spin positive-parity states are something of a puzzle and require a knowledge of the role of the Fermi energy for these states and an understanding of the mechanism of j-mixing. The latter has been treated in the quasiparticle-cluster phonon coupling model for the odd-mass Au isotopes[5] and for the mixing of two j-values in a triaxial rotor model for ^{187}Ir (ref. 6). It appears that a very complete characterization of the excited states

[4] E. F. Zganjar, J. L. Wood, R. W. Fink, and other UNISOR coauthors, Phys. Lett. 58B, 159 (1975).

[5] V. Paar, Ch. Vieu, and J. S. Dionisio, preprint (1975).

[6] A. Faessler and H. Toki, Phys. Lett. 59B, 211 (1975).

up to $\approx$ 1.5 MeV of at least some of the odd-Au nuclei is necessary to make a choice among the different particle-core coupling schemes for low-spin states. This is being pursued in the case of ^{193}Au (see below) and seems to favor a relatively pure-j nucleon coupled to a triaxial rotor, even for cases where j is low and in principle should be mixed. The role of the Fermi energy in defining the effective core is critical, since it determines the particle or hole (or quasiparticle) character of the odd nucleon and further defines[3] the principal value of the Nilsson quantum number Ω. This is currently being explored experimentally in the pure-j case of the $i_{13/2}$ quasiparticle states in the odd-mass Pt and Hg isotopes. Mixed-j cases are also being extensively investigated in ^{189}Pt and the odd-mass Hg isotopes (see below). Again, in ^{189}Pt single-j nucleons coupled to a triaxial rotor seem to be favored.

The nature of the excited 0+ states in the even-mass Pt and Hg isotopes is also being explored by applying the concept of an effective core. In this case, the odd nucleon is acting as a probe by coupling to the core in an excited 0+ configuration and the coupling degrees of freedom reveal the structure of the 0+ configuration. For example, if the configuration is deformed, a rotational band structure is seen, as appears to happen in ^{187}Au (see below).

2.1.2 The Triaxial Rotor Model

We have pursued a thorough investigation of the applicability of the triaxial rotor to the high-j states in the odd-mass Ir, Au, and Tl isotopes. The systematic trends of the $h_{11/2}$ triaxial band through the odd-Au isotopes[4] and of the $h_{9/2}$ triaxial band through the odd-Tl isotopes[7] are very stable. This can be interpreted[3] in terms of $h_{11/2}$ holes and $h_{9/2}$ particles coupling to even Hg oblate-triaxial cores. In contrast, the trend of the $h_{11/2}$ triaxial band through the odd-Ir isotopes[8] and of the $h_{9/2}$ triaxial band through the odd-Au isotopes[9]

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[7] L. L. Riedinger, et al., Report ORNL-5137 (1976); p. 59

[8] C. Sebille-Schuck, et al., Report CSNSM-1973/75; p. 21

[9] J. L. Wood, et al., Report ORNL-5137 (1976); p. 11

---

is a rapidly changing one, reflecting the coupling of $h_{11/2}$ and $h_{9/2}$ particles to even-Pt cores that change from oblate triaxial to prolate triaxial shapes as the neutron number decreases. The $h_{9/2}$ particle and $h_{11/2}$ hole bands in ^{189}Au dramatically illustrate[1] the particle-hole symmetry that is basic to the triaxial rotor. The question of triaxiality of the $h_{9/2}$ bands in the odd-Ir isotopes remains open[6].

The exploration of j-mixing in the triaxial rotor is limited to a treatment[6] of some low-spin members of the $h_{9/2}$ band in ^{187}Ir, which may have some $f_{7/2}$ contribution. We have accumulated evidence that the $f_{7/2}$ state lies about 700 keV above the $h_{9/2}$ state throughout the odd-Au and odd-Tl isotopes (see below), and thus, a mixed-j treatment is desirable. The question of the validity of a triaxial rotor description for the bands built on low-spin states in the odd-Au isotopes is important and has not yet been answered. The $s_{1/2}$, $d_{3/2}$, and $d_{5/2}$ orbitals contribute to these structures, and the $d_{3/2}$ state appears to have a well-defined triaxial band[9)]. A choice between the triaxial rotor and competing theories, in particular the quasiparticle-cluster phonon coupling model[5)] and the microscopic model of Hecht[10)] based on the pseudo-SU(3) coupling scheme, needs to be made for the further development of collective models in this region.

[10] K. T. Hecht, Phys. Lett. 58B, 253 (1975).

The role of the Fermi energy and the Nilsson quantum number Ω, in the triaxial rotor model, has been explored only in the $i_{13/2}$ band of ^{191}Pt (ref. 11). Before

[11] T. L. Khoo, et al., Phys. Lett. 60B, 341 (1976).

the model can help understand the way in which Nilsson model states develop out of spherical shell model states, a substantial amount of data is needed. The low-spin members of the $i_{13/2}$ bands in ^{189}Pt and the odd-mass Hg isotopes are being sought experimentally (see below) to help clarify these points.

2.1.3 The Shell Model and Intruder States

We have observed the $h_{9/2}$, $i_{13/2}$, and $f_{7/2}$ odd-proton states in many of the odd-mass Ir, Au, and Tl isotopes. These states come from the $Z > 82$ shell. Their appearance at low energies (particularly the $h_{9/2}$ state) in these nuclei with $Z < 82$ is not easily explained by the Nilsson deformed shell model. The band structure built upon these states suggest their deformations are half the magnitude required for them to appear near the Fermi energy of the $Z < 82$ nuclei. In the odd-Tl isotopes, Newton, et al.[12)] have argued that there is a

[12] J. O. Newton, et al., Nuclear Phys. A236, 225 (1974).

large pairing correlation blocking effect, such that the excitation of the odd proton to the $h_{9/2}$ orbital opens the $Z \leq 82$ shell to pairing correlations. Such a mechanism[12)] would be less pronounced in the odd-Au nuclei, where the odd nucleon does not completely block the shell to pairing correlations. However, the $h_{9/2}$ state lies even closer to the Fermi energy in the odd-Au isotopes and is the ground state[13)] in ^{185}Au.

[13] C. Ekström, reported at the 3rd Int. Conf. on Nuclei Far From Stability, Cargese, Corsica, France, May, 1976

We have systematically explored the published data on the regions around closed shells for such intruder states to find a similar phenomenon for Z = 50.[14] The $g_{9/2}$ hole state and $g_{7/2}$ particle state are well established in the odd-mass Sb and In isotopes, respectively. They have been argued[15,16] to be evidence for shape coexistence in these nuclei. We have considered[14] contributions from a quadrupole pairing deformation degree of freedom[17], as well as a quadrupole deformation degree of freedom, in an attempt to correlate the data that we have compiled on intruder states (see below). The $g_{9/2}$-hole state is also seen in the odd-iodine nuclei and the $g_{7/2}$-particle state in the odd-Ag nuclei. The $d_{3/2}$-hole state is well established

[14] J. L. Wood and R. W. Fink, "Intruder States and the Quadrupole Pairing Force," Phys. Rev. Lett. (submitted, 1976); ORO-3346-199.

[15] W. D. Fromm, et al., Nuclear Phys. A243, 9 (1975)

[16] W. Dietrich, et al., Nuclear Phys. A253, 429 (1975

[17] I. Ragnarsson and R. A. Broglia, Nuclear Phys. A263, 315 (1976)

as a low-energy excitation in the $f_{7/2}$ shell, and the $h_{11/2}$-hole state rapidly descends to the vicinity of the Fermi energy in the N = 85, 87, and 89 nuclei. The current state of our compilation suggests the phenomenon to be more pronounced for odd-proton nuclei than for odd-neutron nuclei.

The most remarkable feature of these intruder states, and the most difficult to explain (see below), is the rapid change in their position relative to the Fermi energy as a function of neutron number. We have observed this change to follow a very distinct parabola-like trend in the odd-Tl isotopes[18] with a minimum at A = 189. This minimum shifts to A $\leq$ 185 in the odd-Au isotopes (there are no data on ^{183}Au and lighter Au isotopes). Such states clearly need thorough

[18] A. G. Schmidt, G. M. Gowdy, J. L. Wood, R. W. Fink, and other UNISOR coworkers, "New Isomers of ^{185}, ^{187}Tl and the Departure of the $h_{9/2}$ Intruder State," Phys. Rev. C (submitted, 1976); ORO-3346-194

exploration throughout the mass surface, in order that the occurrence of isomerism, due to these intruder states, can be predicted and the structure of nuclei near closed shells systematized and understood.

2.1.4 Quadrupole Pairing

Evidence for a residual quadrupole pairing force first came from two-nucleon transfer studies in the region of ^{208}Pb (see, for example, ref. 19).

[19] R. A. Broglia, et al., Adv. Nuclear Phys. 6, 287 (1973)

Besides the observation of the strong population of excited 0+ states in this region, which is attributed to the collective effects of the residual monopole pairing force, the strong population of excited 2+ states is also observed and is interpreted as due to a residual quadrupole pairing force. These effects are essentially dynamic and are called monopole and quadrupole pairing vibrations, a close analogy being drawn[19] with the quadrupole shape vibrations of spherical nuclei produced by the residual quadrupole force.

Just as a residual quadrupole force produces static quadrupole shape deformations away from closed shells, so the residual monopole pairing force produces the so-called "static pairing deformations" or smeared (deformed) Fermi surface away from closed shells. The residual quadrupole pairing force reduces the pairing correlations between a nucleon in a prolate (down-sloping) orbital and a nucleon in an oblate (up-sloping) orbital of the Nilsson diagram by about a factor of ten[19] relative to the pairing correlation between nucleons in like orbitals. This can result in two distinct pairing configurations in place of the single monopole pairing configuration. The residual quadrupole pairing force causes pairs of like nucleons to correlate their motion in orbitals with specific alignment (prolate or oblate) in the deformed field; whereas, the residual monopole pairing force produces correlated motion of pairs among all orbitals equally.

Such a static manifestation of the residual quadrupole pairing force has been observed[17,20] in the actinide region where a system of prolate neutron orbitals is

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[20] A. M. Friedman, et al., Phys. Rev. C9, 760 (1974)

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completely filled and a system of oblate neutron orbitals is partially filled. The (p,t) reaction can pick up a pair of neutrons from either the oblate or prolate pairing configuration, whereas the pair of neutrons from the (t,p) reaction can only enter the system of oblate orbitals because of the Pauli Exclusion Principle. Further, the presence of an unpaired neutron in the system of oblate orbitals produces a blocking effect on the oblate pairing correlations but not on the prolate pairing correlations, with the result that the two pairing configurations are closer together in energy in the odd-neutron nuclei than in the even-neutron ones (where there is no blocking effect). A study[21] of (p,t) reactions in the vicinity of ^{160}Dy reveals that a similar phenomenon occurs there. A recent theoretical study[22]

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[21] J. V. Maher, et al., Phys. Rev. C6, 358 (1972)

[22] S. E. Larsson, et al., Physica Scripta 10A, 65 (1974).

suggests that it is important to consider the effects of a residual quadrupole pairing force in estimating fission barrier heights for superheavy elements.

We are pursuing the interpretation of intruder states in terms of an effective residual quadrupole pairing force[14]. In the case of odd-mass nuclei, the effect of a quadrupole pairing force is to reduce the blocking effect of the odd nucleon when it occupies a prolate (oblate) orbital in Fermi surface regions that are predominantly made up of oblate (prolate) orbitals. As a result, such states (where the odd nucleon has a reduced blocking effect) appear at an energy 0.7 to 1 MeV lower than states involving odd nucleons that block the pairing correlations. In a sense, the odd nucleon is being used as a probe of the pairing density through its blocking effect on the pairing correlations. Although this quadrupole pairing picture seems to be able to explain the appearance of intruder states at low energies, the rapid variation of intruder state energies with changing neutron number relative to the Fermi energy remains a puzzle. We are pursuing explanations that take into account the near parabolic shape of this trend in the odd-Tl isotopes[18].

A variety of phenomena that would be produced by a residual quadrupole pairing force remain to be systematically explored. The coexistence of prolate and oblate pairing configurations in actinide nuclei has been observed to produce dramatically different (p,t) and (t,p) transfer reaction cross sections[17]. Such behavior should be widespread, although two-proton transfer reactions are experimentally more difficult to explore, since the (^{3}He,n) and (n,He^{3}) reactions do not involve charged particles in both entrance and exit channels, and the use of heavier ions involves complex transfer and Coulomb excitation mechanisms. In addition, single nucleon transfer reactions should show anomalously high or low nucleon (pair) occupancy for intruder states in doubly-even (target) nuclei. This is because these orbitals cannot participate in the mixed pairing configuration of the nuclear ground state due to the reduced pairing correlations between nucleons in these orbitals and nucleons in orbitals close to the Fermi energy. The nature of multi-particle excitation into intruder states also needs to be explored. There is evidence for anomalously low energy three-particle states in the odd-Tl isotopes[23], and the excitation of pairs of nucleons into these orbitals should give rise to pairing isomers[17]. It is probable that the deformed excited states in the doubly-even Hg isotopes[24] involve the promotion of proton pairs into the $h_{9/2}$ and $i_{13/2}$

[23] R. Lieder, KFA Jülich, private communication (1976)

[24] J. H. Hamilton, R. W. Fink, G. M. Gowdy, J. L. Wood, and other UNISOR coauthors, Phys. Rev. Lett. 35, 562 (1975);
J. D. Cole, et al., Report ORNL-5137 (1976); p. 9
J. L. Wood, R. W. Fink, and other coauthors, invited paper, 3rd Int. Conf. on Nuclei Far from Stability, Cargese, Corsida, France, May (1976)

orbitals. For example, a simple test of this picture would be a search for the coupling of the deformed ^{188}Hg core state to an odd proton in the $h_{9/2}$ orbital in ^{189}Tl. The odd proton should block the formation of the deformed core state and either raise its energy or prevent its formation altogether. A recent calculation of deformed shapes in the doubly-even Hg isotopes[25)] notes the importance of a

[25] S. G. Nilsson, et al., Nuclear Phys. A222, 221 (1974)

residual quadrupole pairing force in producing the deformed potential-energy minima. It is also probable that such orbitals play a major role in producing the backbending of yrast bands. The decoupled pairs of the Stephens-Simon model[26)] can occupy these

[26] F. S. Stephens and R. S. Simon, Nuclear Phys. A183, 257 (1972)

orbitals without severely blocking the pairing correlations and thus are favored to appear at lower energy. The $h_{9/2}$ proton orbital is believed to play a major role in producing the backbending of the yrast states in the Re and Os isotopes[27)].

[27] A. Neskakis, et al., Nuclear Phys. A261, 189 (1976)

(J. L. Wood)

2.2 Current Experimental Investigations

Our experimental decay scheme studies continue to be dominated by the investigation of radioactive sources produced at UNISOR using γ-, ce$^-$, and x-ray multiscaling, $\gamma\gamma t$-, e$^-\gamma t$-, and $\gamma x t$-coincidence spectroscopy. We have continued with studies in the mass chains A = 183 through 197 using Ta, W, and Re targets and beams of $^{16}O^{+5}$ and $^{14}N^{+5}$ ions with energies up to 160 MeV (^{16}O) and 180 MeV (^{14}N). The Ta and Re targets were of natural isotopic abundance, the Re being an alloy with Mo; the W targets were enriched 94.47% ^{172}W and 92.96% ^{180}W (natural abundance 0.135%). The latter targets were fabricated by R. L. Mlekodaj of UNISOR using electron bombardment of $^{180}W_2O_3$ powder sandwiched between graphite felt to reduce the oxide to metallic layers strongly bonded onto the graphite felt. The reactions yielding the most neutron-deficient isotopes were $^{180}W(^{14}N,p10n)^{183}Hg$, $^{180}W(^{14}N, 10n)^{184}Tl$, and $^{182}W(^{16}O, 7n)^{191}Pb$. The greatest amount of effort has been devoted to completing detailed decay scheme studies in the heavier odd-mass Ir, Pt, Au, Hg, and Tl isotopes and to characterizing the main decay branches of short-lived species in the A = 185 region, with specific emphasis on answering questions raised by our systematics studies. The target/ion source arrangements were of the standard in-beam type as described in the Annual Report last year. Recent technical development at UNISOR is reviewed in refs. 28 and 29).

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[28] H. K. Carter, R. A. Braga, and other UNISOR coauthors, Nucl. Instr. & Meth. (submitted, 1976) (ORO-3346-192).

[29] R. L. Mlekodaj, et al. Report ORNL-5137 (1976); p. 24

In the past year we have greatly improved our on-campus data reduction facilities, particularly with the acquisition of our own terminal with CRT visual display (see Sect. 6.1), and consequently we have reduced the time spent at UNISOR to analyze data.

This year we have arranged the following detailed descriptions of our experimental work under the categories given in Sect. 2.1, so that each experimental investigation supports a central question of nuclear structure. We hope this new format for our annual report will serve to emphasize the fundamental importance of the experimental work.

On-campus studies of the decay schemes of radioactive sources produced in the Georgia Tech Research Reactor are included under these categories, since they are extensions to neutron-rich nuclei of our nuclear systematic investigations. Lifetimes in the range 20 nsec to 800 nsec can now be routinely extracted from our $\gamma\gamma t$-coincidence data (see Sect. 2.2.5).

2.2.1 Particle-core Coupling and Effective Cores

Information on particle-core coupling and the effective core has come from almost all of our experiments. The coupling of the $h_{11/2}$ holes and the $h_{9/2}$ particles to even Hg and Pt cores, respectively, as seen in the odd-Au isotopes, has been well characterized in our studies of the decays of the high- and low-spin odd-Hg isomers. The $^{189m}Hg(8.7\ min)\rightarrow^{189}Au$ and $^{189g}Hg(7.7\ min)\rightarrow^{189}Au$ decay schemes are completed and are being prepared for publication[30]. The unique particle-hole symmetry of the $h_{9/2}$ and $h_{11/2}$ bands in ^{189}Au have been the subject of a preliminary communication[1]. The very similar decays ^{191m}Hg(51 min)→^{191}Au and ^{191g}Hg(35 min)→ ^{191}Au are also completed and a paper is in preparation[31]. The coupling of the

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[30] J. L. Wood, E. F. Zganjar, and UNISOR coworkers, "Decay of ^{189m,g}Hg: Coupling of Particles and Holes," (to be published) (ORO-3346-176)

[31] J. L. Wood, G. M. Gowdy, and UNISOR coworkers, "Decay of ^{191m,g}Hg to ^{191}Au," (to be published) (ORO-3346-177)

$h_{11/2}$ holes and the $h_{9/2}$ particles to even Pb and Hg cores, respectively, in ^{197}Tl has been confirmed in studies of the ^{197m}Pb(42 min)→^{197}Tl and ^{197g}Pb(68.5 min)→ ^{197}Tl decay schemes, which are in the final stages of analysis[32]. The very stable trend in the odd-Au nuclei[4] have been extended to ^{187}Au through a study of the ^{187m}Hg(2.3 min)→^{187}Au decay scheme which is still in progress (& see below) (J. L. Wood, M. Grimm, D. A. McClure, and UNISOR coworkers). A very detailed investigation of the low-spin states in ^{193}Au has also been made with a study of the ^{193g}Hg(4.6 h)→ ^{193}Au decay scheme, which is now nearly completed[33]. As mentioned in last year's

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[32] L. L. Collins, M. S. Rapaport, J. L. Wood, R. W. Fink, with other UNISOR coauthors Bull. Am. Phys. Soc. 21 (in press, 1976). (ORO-3346-198); full paper in preparation; M. S. Rapaport, and UNISOR coworkers, "Isomerism in ^{197}Pb." (to be published) (ORO-3346-200)

[33] D. A. McClure, J. L. Wood, and R. W. Fink, Bull. Am. Phys. Soc. 21, 559 (1976); full paper in preparation

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Annual Report, we have been able to produce large yields of low-spin ^{193g}Hg relative to high-spin ^{193m}Hg by entering the A = 193 mass chain at Pb and Tl. We believe that a detailed characterization of the low-spin states in ^{193}Au will reflect the low-spin structure of all of the odd-Au isotopes under study, in light of the stable trends observed so far[4] for the $h_{11/2}$ bands and the states of positive parity. It is crucial that all of the low-spin states (and particularly those with positive parity) at low energy (< 1.0 MeV) be seen, in order to distinguish between quasiparticle-rotor[2,3] and quasiparticle-vibrator[5] coupling schemes.

The coupling of the $i_{13/2}$ quasiparticle to the core in the odd-Pt and odd-Hg isotopes provides a pure-j case for studying the role of the Fermi energy in defining the effective core. Although the high-spin states of the $i_{13/2}$ bands have been well studied by in-beam γ-ray spectroscopy in the odd-Pt (refs. 34,35,36) and odd-Hg (refs. 37, 38) nuclei, the only low-spin members of an $i_{13/2}$ band observed so far have been in the $^{191}Au \rightarrow ^{191}Pt$ decay[39)], and in a very detailed light-ion in-beam γ-ray spectroscopic study[40)] of ^{197}Hg. The location of the

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[34] M. Piiparinen, et al., Phys. Rev. Lett. 34, 1110 (1975).

[35] T. L. Khoo, et al., Phys. Lett. 60B, 341 (1976).

[36] M. A. Deleplanque, et al., J. Physique (Paris) Colloq. 36, C5, 97 (1975).

[37] D. Proetel, et al., Nuclear Phys. A226, 237 (1974).

[38] R. M. Lieder, et al., Nuclear Phys. A248, 317 (1975).

[39] M. Piiparinen, et al., Nuclear Phys. A265, 253 (1976).

[40] D. Venos, et al., Report Rossendorf ZfK-295 (1975); p. 40.

Fermi energy is evidently critical in the interpretation[35)] of the $i_{13/2}$ band in ^{191}Pt. In order to get a comprehensive picture, the systematics of the band structure as a function of neutron number (changing Fermi energy) is needed. We are searching for evidence of $i_{13/2}$ band population in the odd-Pt and odd-Hg nuclei in the decays of the Au and Tl isotopes. The decay schemes of $^{189m}Tl(1.4\ min) \rightarrow ^{189}Hg$ (ref. 41), $^{191m}Tl(5.5\ min) \rightarrow ^{191}Hg$(ref. 42), $^{193m}Tl(2.1\ min) \rightarrow ^{193}Hg$ and $^{193g}Tl(21\ min) \rightarrow ^{193}Hg$ (ref. 43), $^{195}Tl(1.2\ h) \rightarrow ^{195}Hg$ (ref. 44), and $^{197}Tl(2.8\ h) \rightarrow ^{197}Hg$ (G. M. Gowdy, M. S. Rapaport, and R. A. Braga) are nearing completion, but no clear evidence for

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[41] E. F. Zganjar, J. L. Wood, R. W. Fink, G. M. Gowdy, and other UNISOR coworkers, Bull. Am. Phys. Soc. 19, 1125 (1974); full paper in preparation.

[42] G. M. Gowdy, J. L. Wood, R. W. Fink, and UNISOR coauthors, Bull. Am. Phys. Soc. 19, 1125 (1974); full paper in preparation.

[43] A. G. Schmidt, G. M. Gowdy, and R. W. Fink, Bull. Am. Phys. Soc. 21, 559 (1976); full paper in preparation.

[44] G. M. Gowdy, J. L. Wood, R. W. Fink, and UNISOR coworkers, Bull. Am. Phys. Soc. 21, 559 (1976).

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population of the $i_{13/2}$ bands has yet been found. The structure of the odd-Hg isotopes constitutes the PhD thesis research of Mr. G. M. Gowdy. The decay schemes of $^{189m}Au(4.5\ min) \rightarrow ^{189}Pt$ and $^{189g}Au(28\ min) \rightarrow ^{189}Pt$ (J. L. Wood, M. Grimm, D. A. McClure, and R. A. Braga) and $^{187}Au(8.5\ min) \rightarrow ^{187}Pt$ (J. L. Wood) are in progress, but population of the $i_{13/2}$ bands has not yet been confirmed. In the study of the decay of $^{189m}Au(4.5\ min)$ we have used sources of unseparated masses obtained via the UNISOR He-gas jet transport system[45)] following the $^{181}Ta(^{12}C,4n)^{189}Au$ reaction,

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[45] H. K. Carter, J. L. Wood, and UNISOR coworkers, Report ORNL-5137 (1975); p. 121.

because entry of the A = 189 mass chain must be made at Hg or Tl, in order to effect mass separation, and the short-lived ^{189m}Au activity is consequently masked by its ^{189m}Hg(8.7 min) parent under such circumstances.

Within our effective core picture, an interesting question is whether or not excited 0+ states show couplings to an odd nucleon, reflecting collective core degrees of freedom associated with this 0+ excitation. Low-lying 0+ states have been observed in $^{182-188}Pt$ (refs. 46,47), $^{184-188}Hg$ (ref. 24), and ^{200}Hg (ref. 48).

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[46] M. Finger, et al., Nuclear Phys. A188, 369 (1972).
[47] M. Caillau, et al., J. Physique (Paris) Lett. 35, L-233 (1974).
[48] D. Breitig, et al., Phys. Rev. C9, 366 (1974).

We have looked for evidence of the couplings involving excited 0+ core states for $^{186}Pt \otimes h_{9/2}$ and $^{188}Hg \otimes h_{11/2}$ in ^{187}Au, $^{188}Pt \otimes h_{9/2}$ in ^{189}Au, and $^{200}Hg \otimes h_{11/2}$ in ^{199}Au. In the latter case, we are studying the $^{199}Pt(30\ min) \rightarrow {}^{199}Au$ decay scheme using thermal neutron activated samples of ^{199}Pt produced from enriched ^{198}Pt in the Georgia Tech Research Reactor (D. A. McClure and J. L. Wood). In our studies[30)] of ^{189}Au, we see a high density of levels 770 - 830 keV above the $h_{9/2}$ level, many of which we cannot interpret as $h_{9/2}$ band members (although they exclusively de-excite into the $h_{9/2}$ band). The first excited 0+ state in ^{188}Pt is located at 798 keV above the ground state, and we are tempted to interpret at least one of these states in ^{189}Au as due to the coupling of the $h_{9/2}$ proton with this 0+ core excitation. In our studies (see above) of ^{187}Au, we have not yet seen evidence for couplings of the $h_{11/2}$ and $h_{9/2}$ protons to the 0+ excited core states. Since recent target developments and cyclotron beam improvements now permit a factor of 5 (estimated) increase in the activity of ^{187m}Hg, we plan to continue with our $^{187m}Hg \rightarrow {}^{187}Au$ decay scheme studies in search of these couplings (J. L. Wood and D. A. McClure). However, in ^{187}Au, we do see relatively low-energy 11/2+ and 13/2+ states at 967 and 1149 keV, respectively, that do not follow the systematic trend[4)] of the positive parity states through $^{195-189}Au$. We assign the 11/2+ and 13/2+ members of the $d_{3/2}$ band in ^{187}Au at 1120 and 1343 keV, respectively, to be compared with 1112 and 1420 keV in ^{189}Au. It is possible that these anomalously low 11/2+ and 13/2+ states are the coupling of the ^{188}Hg core 0+ state at 825 keV to an odd proton in a positive parity state (possibly a strong deformed Nilsson state). Clearly the structure of ^{187}Au may provide an abundance of information on shapes and coupling schemes. A study of the

$^{185m}Hg(18\ sec) \rightarrow {}^{185}Au$ and $^{185g}Hg(50\ sec) \rightarrow {}^{185}Au$ decay schemes is underway as part of the PhD thesis research of Mr. M. Grimm* (and see below).

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*Mr. Grimm has been awarded an ORAU Fellowship in support of this research at UNISOR

Finally, we are investigating the onset of strong coupling and the residual Coriolis interaction in the nuclei ^{185}Ir and ^{151}Pm. The former nucleus is being studied in the $^{185m}Pt(1.2\ h) \rightarrow {}^{185}Ir$ and $^{185g}Pt(33\ min) \rightarrow {}^{185}Ir$ decay schemes, following entry of the A = 185 mass chain at Hg. The data are in the final stages of analysis (M. S. Rapaport). The latter nucleus is being studied by the decay of $^{151}Nd(12\ min) \rightarrow {}^{151}Pm$, following thermal neutron activation of ^{151}Nd sources from enriched Nd^{150} targets in the Georgia Tech Research Reactor. This study is in its preliminary stages (C. Papanicopopulos, D. A. McClure, and J. L. Wood).

2.2.2 Triaxial Rotor Model

Our investigation of particle-core coupling in the odd-mass Au and Tl nuclei has led to a detailed evaluation of the triaxial rotor as a description of the collective degrees of freedom of the core. The $h_{11/2}$ hole bands in the odd-Au nuclei and the $h_{9/2}$ particle bands in the odd-Tl nuclei are well described by a single-j nucleon (hole or particle) coupled to a triaxial rotor core. We have made very thorough investigations of these bands in our studies of ^{189}Au (ref. 30), ^{191}Au (ref. 31), and ^{197}Tl (ref. 32). Our study of low-spin states in ^{193}Au (ref.33) has also located some new $h_{11/2}$ band members; the low-spin members of a triaxial band are particularly sensitive to the model parameters. Our results agree well with a triaxial rotor picture up to the pairing energy, where the single-particle (-hole) picture is no longer completely valid due to the appearance of three-particle degrees of freedom. A study of the $^{191m}Pb\ (2.0\ min) \rightarrow {}^{191}Tl$ decay scheme has been started to extend the systematics[7)] of the $h_{9/2}$ triaxial band through the odd-Tl isotopes*. This work is also part of the PhD thesis research of Mr.

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*We have found, in the course of this work, that the presence of graphite felt in the in-beam ion source (as a reaction recoil catcher) strongly retains Pb activity unless a high temperature or CCl_4 injection is used. A hollow-cathode ion source is under development at UNISOR to provide the high temperatures needed to obtain good yields of mass separated Pb isotopes in this region of low production cross sections.

M. Grimm (see above). The interpretation of the $h_{9/2}$-particle band systematics in the odd-Au nuclei as a transition in shape from oblate triaxial to prolate triaxial as the neutron number decreases[3)] is well supported by our studies of ^{189}Au and ^{191}Au. Our study of the $h_{9/2}$ band in ^{187}Au has extended this systematic (see above), and this is now being continued even further with our study of the decays of ^{185m,g}Hg to ^{185}Au (see above). A recent atomic beam measurement[13)] of the ground state spin (5/2) of ^{185}Au suggests that the $h_{9/2}$ proton is approaching strong coupling to a prolate core in this nucleus. The current study of the decays of ^{185m,g}Pt to levels in ^{185}Ir promises to answer the question of whether or not the $h_{9/2}$ proton particle couples to a triaxial or an axially-symmetric core (see above). A choice needs to be made among an axially-symmetric rotor[2,49)], an axially-symmetric rotor with hexadecapole deformation[50)], a single-j particle coupled to a triaxial rotor[3)], or a triaxial rotor with j-mixing[6)].

[49] M. E. Bunker and C. W. Reich, Rev. Modern Phys. 43, 348 (1971).
[50] F. T. Baker and D. Goss, Phys. Rev. Lett. 36, 852 (1976).

The success of the triaxial rotor for cases of pure-j coupling to the doubly-even Pt and Hg cores has caused us to make detailed studies of the states which have the low-j parentage $s_{1/2}$, $d_{3/2}$, and $d_{5/2}$ in the case of protons, and $p_{1/2}$, $p_{3/2}$, $f_{5/2}$, $f_{7/2}$, and $h_{9/2}$ in the case of neutrons, and hence can be expected to have mixed-j values. Our studies of the excited states of $^{187-193}$Au indicate well-defined band structure built on a 3/2+ state[4,9)], which can be described by a pure-j = 3/2 ($d_{3/2}$) proton quasiparticle coupled to a triaxial core. We expect our detailed studies of ^{193}Au to answer the question of whether or not bands built on the $s_{1/2}$ and $d_{5/2}$ proton quasiparticle states appear as pure-j couplings to a triaxial core (see above). Our studies of the excited states of $^{189-197}$Hg (see above) show a more complex systematic trend (see, for example, ref. 51), probably

[51] G. M. Gowdy, J. L. Wood, R. W. Fink, and UNISOR coauthors, Report ORNL-5137 (1975); p. 14.

due to the fact that the Fermi energy is changing in this systematic sequence. We are not yet able to classify the negative parity states of the odd-Hg isotopes in terms of band structures, mainly because there is a lack of data permitting the location of the higher spin (J > 7/2) states. We are concentrating on the levels of ^{193}Hg populated in the decay of high-spin (J = 9/2) ^{193m}Tl and low-spin (J = 1/2) ^{193g}Tl (ref. 43) to help find all of the low-lying states up to J = 11/2. In the case of the other odd-Tl decays, we have only been able to observe[51)] a single beta-decaying state. In the ^{189m,g}Au$\rightarrow$^{189}Pt decay scheme studies (see above), we have a tentative level scheme for ^{189}Pt which suggests well-defined band structures built on states of 1/2-, 3/2-, 5/2-, and 9/2-. Conversion electron data are needed to confirm spins and parities of band members. A vacuum seal design to separate the tape transport stations for the electron counting and the collection of activity deposited by the He gas jet is under development[45)] at UNISOR.

2.2.3 The Shell Model and Intruder States

The $h_{9/2}$ proton particle state is well established throughout the odd-mass Au and Tl isotopes by our UNISOR work[1,9,30,31)] and other studies[7,12,52,53)].

[52] L. L. Riedinger, et al., Report ORNL-5137 (1975); p. 59.

[53] V. Berg, et al., J. Physique (Paris) 36, 613 (1975).

Our recent investigation of ^{187}Tl and ^{185}Tl reveal isomeric decay to the ground state, similar to that observed in ^{193}Tl and ^{195}Tl, respectively[18)]. We infer from our studies[41,42)] of the beta-decay of ^{189}Tl(1.4 min) and ^{191}Tl(5.5 min) that these are the $h_{9/2}$ states*, indicating that the $h_{9/2}$ state lies below the 3/2+ state in ^{189,191}Tl

*This was confirmed using beta-decay systematics which predict that if the 1.4 min beta-decay in ^{189}Tl and 5.5 min beta-decay in ^{191}Tl were from the $h_{9/2}$ states, then the 2.1 min $h_{9/2}$ isomer in ^{193}Tl should have a 17% beta-decay branch. We subsequently observed a $\approx$ 20% beta-decay branch from this isomer (J. L. Wood and G. M. Gowdy)

(see Ref. 18, Fig. 1 therein). Thus, in the odd-Tl isotopes, the energy of the $h_{9/2}$ intruder state relative to the ground state follows a parabola-like trend with a minimum at approximately A = 189. The $i_{13/2}$ proton particle state has been tentatively identified in the light odd-Tl isotopes[7,12,52)]. We find evidence for this state in ^{187}Au (see above), ^{189}Au(ref. 30), and possibly ^{191}Au(ref. 31). Based on the odd-proton systematics in the Bi isotopes[54)], we expect the $f_{7/2}$ state

[54] K. A. Erb and W. S. Gray, Phys. Rev. C8, 347 (1973)

for protons to lie between the $h_{9/2}$ and $i_{13/2}$ states in the odd-mass Tl and Au nuclei. Candidates for the $f_{7/2}$ state in ^{189}Au appear in a cluster of levels at 770-830 keV above the $h_{9/2}$ state. Clearly, this region should provide an abundance of information on intruder states. A pilot study of the production of A = 183 activities reveals that the threshold for the $^{180}W(^{14}N,p10n)^{183}Hg$ reaction is $\simeq$ 170 MeV incident energy, thus promising access to a study of these intruder states in ^{183}Au and ^{183}Ir, when the maximum energy of the $^{14}N^{+5}$ beam from ORIC is raised a little from its present maximum of 180 MeV (J. L. Wood).

2.2.4 Quadrupole Pairing

The experimental evidence that we have obtained for a residual quadrupole force is based on the existence of intruder states (see above), which we argue to be due to a blocking effect of the unpaired nucleon (see Sect.2.1.4). The only experiments that are nearly direct tests of a residual quadrupole pairing force are the one- and two-nucleon transfer studies described in Sect. 2.1.4. We will continue to explore quadrupole pairing through the odd-nucleon blocking effect as in the suggested study of ^{189}Tl in Sect. 2.1.4, for example (see discussion in the accompanying Renewal Proposal).

2.2.5 Nuclear Lifetime Measurements

The radiative lifetimes of nuclear states, or more fundamentally, the electromagnetic transition matrix elements, are vitally important to the study of the structure of nuclei. These electromagnetic matrix elements provide a basis for comparison between model wave functions and experiment. The measurement of nuclear lifetimes results in the clarification of nuclear structures, notably in the establishment of the band head members of intruder states which play a critical role in the development of deformed nuclear shapes (see Sect. 2.1.3 above).

Our measurements of mean level lifetimes were undertaken by employing delayed coincidence techniques using Ge(Li) detectors and constant-fraction (CF) discrimination timing. The distribution of all delays, as well as "prompt peaks," was collected simultaneously. The time distribution for the 224.0 keV level in ^{187}Au and the 172.6 keV level in ^{189}Pt relative to the lifetime properties of their respective "prompt" spectra are shown in Fig. 1. Values of 48 ± 5 nanosec and 492 ± 77 nanosec for the lifetimes of the 224.0 and 172.6 keV levels, respectively, were obtained by a linear least-squares analysis utilizing the computer code FRANTIC[55]. These results are in agreement with previously reported values of 50 ± 8 and 464 ± 25 nanosec, resp.[56,57]

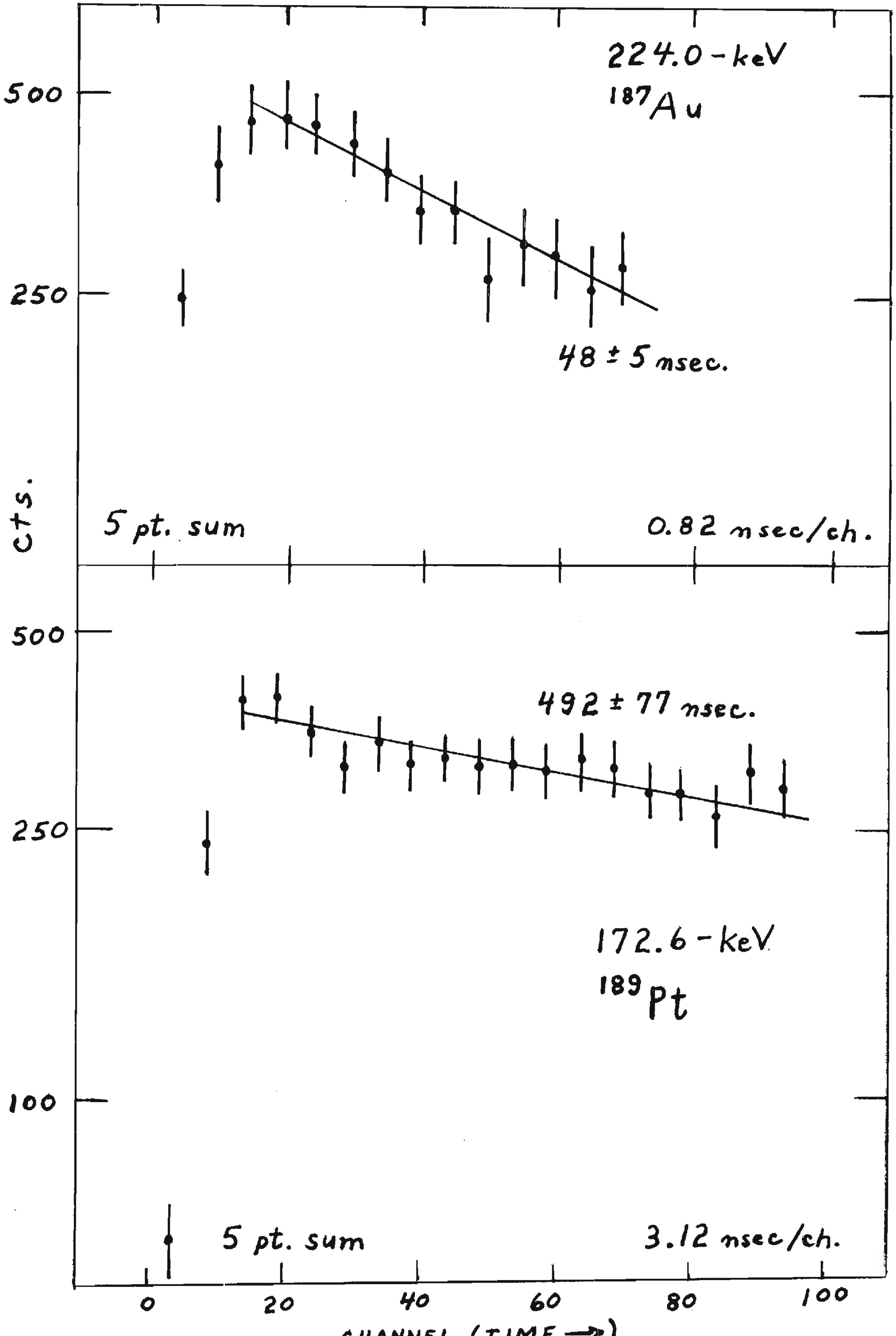
224.0-keV
^{187}Au
48 ± 5 nsec.
5 pt. sum
0.82 nsec/ch.
cts.
500
250
492 ± 77 nsec.
172.6-keV
^{189}Pt
100
5 pt. sum
3.12 nsec/ch.
0
20
40
60
80
100
CHANNEL (TIME →)

Fig. 1

[55] P. C. Rogers, MIT Report No. 76 (1962).

[56] V. Berg, J. Physique (Paris) 36, 613 (1975).

[57] M. Finger, et al., Report CERN 70-29 (1970)

The use of constant-fraction discrimination timing with Ge(Li) detectors limits lifetime measurements to > 10 nanosec. However, the recent addition of state-of-the-art amplitude and rise-time compensation (ARC) timers will permit the extension of this limit to the determination of lifetimes down to $\approx$ 1 nanosec. (R. A. Braga)

On the other hand, to measure lifetimes longer than some 100 μsec, the multiple-time-analysis (MTA) concept of Glatz and Löbner[58)] has been adapted to

[58] J. Glatz and K. E. G. Löbner, Nuclear Instr. & Meth. 94, 237 (1971)

the UNISOR computer-based Tennecomp data acquisition system. This technique is ideal for UNISOR research, since in dealing with weak sources and long lifetimes (> 1 millisec), the use of standard start-stop techniques results in the rejection of additional start pulses occurring during the measuring period, thereby resulting in the rejection of true as well as chance coincidence events. The MTA concept overcomes this serious drawback by measuring the delayed coincidences with essentially no such losses and thereby permitting the measurement of nuclear level lifetimes in the range 10 μsec < τ < 1 sec. A detailed description of the MTA concept was given in our Renewal Proposal of last year (Oct. 31, 1975), and we have been implementing it at UNISOR this year.

As of this writing (September, 1976), hardware for the MTA system consisting of a "real-time" digital clock (designed and constructed in the Georgia Tech chemistry Electronics Shop by G. D. O'Brien), has been successfully interfaced to the UNISOR computer-based data acquisition system. A description of the working principle of this system has been submitted for publication[28)].

(R. A. Braga)

3.0 THE Li^6D SOURCE OF REACTOR-PRODUCED 14-15 MeV NEUTRONS

A final design of a test Li^6D capsule for irradiation of enriched isotopes with 14-15 MeV neutrons in the Georgia Tech Research Reactor has been completed and tested. The basic design was shown in last year's Annual Report (Fig. 9) and consisted of a double-walled stainless steel (Type 304) container with 0.5 mm wall thickness and a 1.8 mm cavity between the walls filled with powdered 96% enriched

Li^6D. Within this container is a container of 2.1 mm thick Pyrex, containing 10% boron, for the triple purpose of absorption of any thermal neutrons passing through the Li^6D layer, insulating the next layer of cadmium from high temperatures, and preventing the Cd from alloying with the stainless steel at high temperature. The Cd container is 5.5 mm thick and serves as a final cutoff of thermal neutrons. The complete elimination of thermal neutrons is desired to avoid (n,γ) reactions in the samples which may interfere with such desired reactions as (n,2n), (n,p), and (n,α). Inside the Cd container is a small capsule of either pure graphite or polyethylene containing the specimen of enriched isotope or natural element to be irradiated with 14-15 MeV neutrons and which can have a maximum volume of 1.5 cm^3, or alternatively, several smaller irradiation capsules can be simultaneously irradiated.

Three test irradiations in the hydraulic rabbit system of the GTRR were made to study the effects of heating or possible overheating. Temperatures in the neighborhood of 600-700°C were found by means of color-changing indicators in the Li^6D layer. Such temperatures represent a satisfactory operating level, since the stainless steel outer shell is water-cooled in the hydraulic rabbit system, and the inner parts of the container (the Cd layer and inner irradiation capsule(s)) are thermally protected by the Pyrex layer.

The system has a set of covers for each layer which are water-tight and which can be quickly opened in a hot cell for fast retrieval of short-lived products to be studied.

In order to avoid the intense radioactivity induced in the stainless steel and the need to schedule the use of the Hot Cell to handle the container after each irradiation, a new container is being built in which the double-walled stainless steel outer shell is being replaced by Zircaloy-2. This will have the advantage of not becoming excessively radioactive and of having a much increased transparency for thermal neutrons, permitting higher flux of thermal neutrons to reach the Li^6D layer, thus increasing the 14-15 MeV neutron flux produced. To reduce the flux depression around the container, the Li^6D layer thickness will be reduced from 1.8 to about 1.5 mm in thickness. More than 99% of thermal neutrons are absorbed in the first 1 mm of Li^6D layer.

With the new container, we plan to measure the 14-15 MeV neutron flux available for irradiation of samples by the activation methods described in last year's Annual Report. This problem constitutes part of the PhD thesis research of Mr. Chris Papanicolopulos.

4.0 X-RAYS FROM RADIOACTIVE SOURCES

4.1 Tables for the Handbook of Spectroscopy

Our "Tables of Experimental Values of X-ray Fluorescence and Coster-Kronig Yields for the K-, L-, and M-Shells" are being updated for publication in the forthcoming second edition of the Handbook of Spectroscopy[59)], which is scheduled for 1977/78 publication. In addition, R. W. Fink is serving on the Editorial Advisory Board for this Handbook. (R. W. Fink with P. V. Rao/Emory)

[59] R. W. Fink and P. V. Rao, in Handbook of Spectroscopy, First Edition, Vol. I, edited by J. W. Robinson (CRC Press, Inc., Cleveland, Ohio, 1974); p 219-229.

4.2 The M4 Conversion Coefficient in ^{193m}Pt Decay

We have completed a precision measurement of the K-shell conversion coefficient of the 135.5 keV M4 isomeric transition in ^{193m}Pt decay. The result, according to the X/γ-ray (XPG) technique, is $\alpha_K = 135.2 \pm 10.5$, which is 3.4% below the theoretical prediction of Hager and Seltzer. Similar deviations have been systematically observed in precise values of E3 and M4 conversion coefficients reported in the literature. This work has been accepted for publication[60)] and constitutes the completed M.S. thesis of Mr. Ali I. Saleh[61)].

(A. I. Saleh, R. A. Braga, and R. W. Fink)

[60] A. I. Saleh, R. A. Braga, and R. W. Fink, Z. Physik (in press, 1976).
[61] A. I. Saleh, M. S. Thesis, Georgia Tech (August, 1976).

4.3 The Total L_2-L_3 Coster-Kronig Transition Probability at Z = 96

The results of this measurement were reported at an American Phys. Soc. meeting and are accepted for publication[62)]. Dual-parameter coincidence measurements were performed with high resolution Si(Li) and intrinsic Ge x-ray spectrometers on the same ^{249}Cf source used by McGeorge and Fink in 1971. The present method eliminates possible errors arising from single-channel windows used earlier. The result is $f_{23} = 0.209 \pm 0.022$ (2σ) at Z = 96. The systematics of the high-Z of f_{23} are discussed in the light of the new value. (D. W. Nix and R. W. Fink)

[62] R. W. Fink and D. W. Nix, Bull. Am. Phys. Soc. 21, 817 (1976) and Z. Physik (in press, 1976).

4.4 L-shell X-ray Fluorescence and Coster-Kronig Yields at Z = 67

A measurement of these yields from the decay of 10.4 hour ^{165}Er is planned as an M.S. thesis problem. The enriched ^{164}Er isotope is on hand for preparation of the source in the Georgia Tech Research Reactor via the (n,γ) reaction.

4.5 Mean L-Shell Fluorescence Yield from Double Vacancy Atomic States in Indium

Experimental studies of the decay of multiple inner-shell vacancy states are scarce because of the inherent difficulty in isolating these species of atoms. The present work involves a collaboration with Prof. P. V. Rao of Emory University and was reported at an American Physical Soc. meeting[63)] and will be submitted for publication. Double vacancy states created in K-Auger electron transitions following the K-capture decay of 115 day ^{113}Sn were studied by observing L x rays in coincidence with the K and L conversion electrons from the 393 keV transition. The ratio of these two coincidence rates is related to the mean L x-ray fluorescence yield $\bar{\omega}_L(XY)$, where X or Y or both are L-shell vacancies. Two (Si(Li) detectors in fast coincidence were employed to observe In L x rays ($\approx$ 3.5 keV) and conversion electrons. It is found that $\bar{\omega}_L(XY)$ is not more than 15% higher than the values estimated on the assumption that there is no difference between the decay properties of single- or double-vacancy atomic states at Z = 49. By measuring the rate of

[63] R. W. Fink, P. A. Indira, I. J. Unus, and P. V. Rao, Bull. Am. Phys. Soc. 21 818 (1976); (to be published in Z. Physik).

K_α-K_α coincidences, relative to the singles K x-ray emission rate, an upper limit of 3.2 ± 0.6% is set for the EC decay of ^{113}Sn to the 647 keV level in ^{113}In.

(P. V. Rao and R. W. Fink)

5.0 MISCELLANEOUS TOPICS

R. A. Braga and R. W. Fink contributed suggestions and material for the First Report[64)] of the International Committee for Radionuclide Metrology, which is chaired by K. Debertin (Physikalisches Technische Bundesanstalt, Braunschweig, West Germany) and in which the U. S. National Bureau of Standards represents this country. In particular, we proposed the need for radioactive standards with known isomeric levels in the μsec to millisec lifetime range for use as "lifetime standards" in calibrating delayed coincidence experiments.

[64] K. Debertin, "Problems in β,γ, and x-ray Spectrometry," First Report, Int. Committee for Radionuclide Metrology, April, 1976.

The requirements for such standards are (1) the parent nuclide must be of reasonably long half-life and be readily available; and (2) the radiations populating and depopulating the isomeric level must be easily measured (e.g. x-rays, ce^-, or γ-rays). Our survey resulted in the following suggested "lifetime standards" for the computer-based method of multiple time analysis (see Sect. 2.2.5):

Transition Energy (keV)	Isomer Lifetime in Nuclide		Parent Nuclide	
394	0.3 millisec	^{88m}Y	85 day	^{88}Zr
304	17 millisec	^{75m}As	120 day	^{75}Se
1633	800 millisec	^{207m}Pb	38 year	^{207}Bi

We also contributed a section on the need for x-ray and γ-ray calibration standards in the region 90 to 150 keV for Ge detectors and for a new standard to replace ^{203}Hg (which appears to undergo photochemical decomposition and loss due to volatilization in some cases and which suffers from a rather inconveniently-short half-life). There is a lack of available absolutely calibrated standards in the curved part of the efficiency curves of Ge detectors in the energy region 90 to 150 keV.

6.0 EQUIPMENT ADDED DURING 1976

We have upgraded our remote terminal access to the Georgia Tech CDC Cyber-70 Computer by replacing an old teletype terminal with an Applied Digital Data System Model 580 CRT terminal. This system has a 12-inch diagonal screen with a refresh rate of 60 frames/sec and operates at switch-selectable rates of 110, 300, 1200, 2400, and 9600 band with choice of full/half duplex. Along with the ADDS terminal, an Andersen-Jacobson Model A242 acoustic coupler was purchased. Since the vast majority of our data analysis requires the use of computer codes, the addition of this CRT terminal has greatly enhanced our data handling capabilities. The response of the system is a considerable improvement over the slow (110 band) rate of the old teletype and is free of the mechanical breakdowns which plague teletypes. (R. A. Braga and D. A. McClure)

We have purchased a Tennelec TC-861 time-to-amplitude (TAC) converter and have ordered a second one, as well as two Canberra Model 1427 amplitude and rise-time compensated (ARC) timing modules. This state-of-the-art timing equipment will be used in the continuation of our lifetime measurement program (see Sect. 2.2.5) both on-campus and at UNISOR. (R. A. Braga)

During the past year a Princeton Gamma-Tech Ge(Li) γ- and x-ray detector was acquired. This detector has the specifications: 1.68 keV FWHM at 1332 keV, 754 eV FWHM at 121.9 keV and a peak/Compton ratio of 32.4:1. The efficiency is 6.0% at 1332 keV of that for a 7.5 x 7.5 cm NaI(Tl) detector. A Canberra Model 1412 Research Amplifier module was purchased to mate with this new Ge(Li) detector. (R. A. Braga and R. W. Fink)

An 80 character fast line printer has been added to the three-parameter (4096 x 4096 x 4096 channel) nuclear spectrometer operated by the School of Physics. (D. A. McClure)

7.0 PERSONNEL

Senior Staff:

Dr. R. W. Fink Professor and Principal Investigator

Dr. J. L. Wood, Senior Research Associate
(Oct. 1, 1972 - Present; full-time, 12 months)

Dr. R. A. Braga, Research Associate
(Oct. 1, 1974 - Present; full-time 5 months + half-time 7 months)

Dr. M. S. Rapaport, Research Associate
(Sept. 15, 1974 - November 30, 1976; full-time 10 months)

Dr. D. A. McClure, Assistant Professor (Physics)
(1/2 time 9 months + full-time 2 months

Mr. N. S. Kendrick, Jr., Assistant Professor (Physics)
(1/8 time, 12 months)

Graduate Students:

Mr. G. M. Gowdy (Chemistry). Completing PhD by December, 1976.
(On ORAU Fellowship in residence at UNISOR, Oak Ridge, February 1, 1975 - December, 1976)

Mr. A. I. Saleh (Chemistry). Completed M.S. in August, 1976
(Was supported by a fellowship from Libya; present address: University of Tripoli, Libya)

Mr. W. S. Lewis (Chemistry). Completing M.S. by December, 1976
(1/2 time ERDA to June 30, 1976; 1/2 time teaching assistant since July 1, 1976). Terminated Aug. 27, 1976.

Mr. C. Papanicolopulos (Physics). Continuing PhD thesis research.
(1/2 time ERDA since June 1, 1975)

Mr. M. A. Grimm (Physics). Continuing PhD thesis research. (1/2 time ERDA to August 31, 1976; ORAU fellowship at UNISOR, Oak Ridge, beginning September 1, 1976)

Mr. Bruce Gnade (Chemistry). New student beginning September 1, 1976. (B.S. 1976, St. Louis University). (1/2 time teaching assistant and will join ERDA contract July 1, 1977, or Sept. 1, 1977.

Undergraduate Student:

Mr. Wm. H. Pass (Chemistry). A senior at Georgia Tech participating in nuclear research through special problems course since March, 1976. Will graduate upon completion of B.S. in January, 1977, and plans to join the nuclear chemistry group for graduate work.

8.0 SUMMARY LIST OF PUBLICATIONS, PRESENTATIONS AT MEETINGS, AND OUTSIDE SEMINARS

"Intruder States and the Quadrupole Pairing Force," J. L. Wood and R. W. Fink Phys. Rev. Lett. (submitted, 1976) (ORO-3346-199)

"Isomerism in ^{197}Pb," M. S. Rapaport, R. W. Fink, and UNISOR coauthors, Nuclear Phys. (to be submitted, 1976) (ORO-3346-200)

"High and Low Spin Levels in ^{197}Tl," L. L. Collins, M. S. Rapaport, J. L. Wood, and R. W. Fink, Bull. Am. Phys. Soc. 21 (in press, 1976) (ORO-3346-198) East Lansing, October, 1976.

"Evidence for Quadrupole Pairing Deformation," J. L. Wood and R. W. Fink, Bull. Am. Phys. Soc. 21 (in press, 1976) (ORO-3346-197) East Lansing, Mich, October, 1976.

"New Isomers of ^{185,187}Tl and the Departure of the $h_{9/2}$ Intruder State," A. G. Schmidt, G. M. Gowdy, J. L. Wood, R. W. Fink and UNISOR coauthors, Phys. Rev. C (submitted, 1976) (ORO-3346-194)

"The K-Shell Conversion Coefficient of the 135.5 keV M4 Transition in ^{193m}Pt Decay," A. I. Saleh, R. A. Braga, and R. W. Fink. Z. Physik (in press, 1976) (ORO-3346-193)

"Recent Work at UNISOR on Neutron-Deficient Au, Hg, and Tl Nuclei in the Mass Range $184 \leq A \leq 197$," J. L. Wood, G. M. Gowdy, R. W. Fink, D. A. McClure, M. S. Rapaport, R. A. Braga, and other UNISOR coauthors, Proc. 3rd Int. Conf. on Nuclei far from Stability, May 19-26, 1976 (Invited paper, Cargese, Corsica, France) (ORO-3346-190)

"The Structure of Light Odd-Neutron Hg and Pt Nuclei," E. F. Zganjar, G. M. Gowdy, J. L. Wood, R. W. Fink, and UNISOR coauthors, "ibid (1976). (ORO-3346-188)

"The Structure of Neutron-Deficient Odd-Mass Nuclei in the Au, Tl Region; Evidence for Coexisting Triaxial Shapes and a Two-Component Pairing Force," J. L. Wood, R. W. Fink, and UNISOR coauthors, ibid (1976) (ORO-3346-183)

"The L_2-L_3 Coster-Kronig Transition Probability at Z = 96," R. W. Fink and D. W. Nix, Bull. Am. Phys. Soc. 21, 817 (1976) (Quebec, Canada, June, 1976); Z. Physik (in press, 1976) (ORO-3346-187) and (ORO-3346-191),resp.

"Decay of Mass Separated ^{190}Tl and ^{190}Hg," C. R. Bingham, J. L. Wood, G. M. Gowdy, R. W. Fink, and UNISOR coauthors, Phys. Rev. C (in press, 1976). (ORO-3346-186)

"L X-ray Emission from Double Vacancy Atomic States in Indium," R. W. Fink, P. A. Indira, I. J. Unus, and P. V. Rao, Bull. Am. Phys. Soc. 21, 818 (1976) (Quebec, Canada, June, 1976) (ORO-3346-189)

"Symmetry between Particle- and Hole-Level Systems in ^{189}Au," J. L. Wood R. W. Fink, E. F. Zganjar, and J. Meyer ter Vehn," Phys. Rev. C14, 682 - 684 (1976)

"Mass Differences of Proton-Rich Atoms near A = 116 and A - 190," B. D. Kern, J. L. Wood, G. M. Gowdy, R. W. Fink, and UNISOR coauthors, in Atomic Masses and Fundamental Constants, Vol. 5, edited by J. H. Sanders and A. H. Wapstra (Plenum Publishing Corp, New York, 1976); pp. 81-87

"On-Line Mass Separator Investigation of New Isotope 2.9 sec ^{116}I," G. M. Gowdy, A. C. Xenoulis, J. L. Wood, K. R. Baker, R. W. Fink, with other UNISOR coauthors, Phys. Rev. C13, 1601 - 1608 (1976)

"Decay of ^{193}Pb, A. C. Kahler, J. L. Wood, R. W. Fink, and UNISOR coauthors, Bull. Am. Phys. Soc. 21, 559 (1976) (Washington, D.C., April, 1976) (ORO-3346-185)

"Triaxial Band in ^{195}Tl," L. L. Collins, J. L. Wood, R. W. Fink, and UNISOR coauthors, Bull. Am. Phys. Soc. 21, 559 (1976) (Wash.,D.C., April, 1976) (ORO-3346-184)

"Systematics of the Levels in the Neutron-Deficient Odd-Mass Hg Isotopes," G. M. Gowdy, J. L. Wood, R. W. Fink, E. F. Zganjar, and A. G. Schmidt, Bull. Am. Phys. Soc. 21, 559 (1976) (Washington,D.C., April, 1976) (ORO-3346-181)

"The Decay of Mass Separated ^{193}Tl," A. G. Schmidt, G. M. Gowdy, R. W. Fink, and C. R. Bingham, Bull. Am. Phys. Soc. 21, 559 (1976) (Washington,D.C. April, 1976) (ORO-3346-182)

"Shell Model Systematics near Closed Shells and a Possible New Role of the Pairing Force," J. L. Wood and R. W. Fink, Bull. Am. Phys. Soc. 21, 639 (1976) (Washington, D.C., April, 1976) (ORO-3346-180)

"Particle-Core Coupling in Nuclear Transition Regions," J. L. Wood, Bull. Am. Phys. Soc. 21, 178 (1976) (Auburn, Alabama, Nov., 1975, invited paper)

"Mass Separator Study of the Decay ^{193}Hg$\rightarrow^{193}$Au," D. A. McClure, J. L. Wood, and R. W. Fink, Bull. Am. Phys. Soc. 21, 559 (1976) (Washington,D.C. April, 1976) (ORO-3346-179)

"New Isotope ^{193}Pb and the Structure of ^{193}Tl; Shape Coexistence in ^{188}Hg and in ^{189}Au; New Ion Source; Recent UNISOR Research," J. H. Hamilton, K. R. Baker, R. W. Fink, G. M. Gowdy, J. L. Wood, A. C. Xenoulis, and other UNISOR coauthors, Proc. 24th National Conf. Acad. of Science USSR on Nuclear Spectroscopy and Structure, Leningrad (Jan. 1975); Bull. Acad. Sci. USSR, Phys. 40, 2-17 (1976).

"Deformation, Pairing, and Particle-Core Coupling $76 \leq Z \leq 81$ and $104 \leq N \leq 120$," J. L. Wood and R. W. Fink, Bull. Am. Phys. Soc. 20, 1185 (1975). (ORO-3346-174)

"The Decay of ^{189m,g}Hg: Coupling of Particles and Holes to a Triaxial Core in ^{189}Au," J. L. Wood, R. W. Fink, and UNISOR coauthors, Phys. Rev. C (to be published, 1976). (ORO-3346-176)

"The Decay of ^{191m,g}Hg to ^{191}Au," J. L. Wood, G. M. Gowdy, R. W. Fink, and UNISOR coauthors, Phys. Rev. (to be published, 1976) (ORO-3346-177)

"Crossing of Near-Spherical and Deformed Bands in ^{188}Hg and New Isotopes ^{186,188}Tl," J. H. Hamilton, K. R. Baker, R. W. Fink, G. M. Gowdy, J. L. Wood, A. C. Xenoulis, and other UNISOR coauthors, Phys. Rev. Lett. 35, 562 (1975)

"An Investigation of the L_2-L_3 Coster-Kronig Transition Probability for $63 \leq Z \leq 96$," D. W. Nix and R. W. Fink, Z. Physik A273, 305 (1975).

"Rotation-aligned Coupling and Axial Symmetry in $^{189-195}$Au," E. F. Zganjar, J. L. Wood, R. W. Fink, with UNISOR coworkers, Phys. Lett. 58B, 159 (1975).

Seminar: J. L. Wood, "Review of UNISOR Research," presented June 4, 1976, at Institut für Kernphysik, Universität Mainz, West Germany.

Seminar: J. L. Wood, "Triaxial Bands and Intruder States in the Au and Tl Isotopes," presented June 6, 1976, Institut für Kernphysik, Kernforschungsanlage, Jülich, West Germany.

Participation in related work:

R. W. Fink, International Advisory Board, 2nd Int. Conf. on Inner Shell Ionization Phenomena, held April, 1976, in Freiburg, West Germany.

R. W. Fink, Technical Expert, International Atomic Energy Agency, Vienna, on Proton-induced X-ray Emission Analysis at the Nuclear Research Center Demokritos, Athens, Greece, March/April, 1976 and December/Jan. 1975/76.

R. W. Fink, Member, Editorial Advisory Board, Handbook of Spectroscopy, 2nd Edition, CRC Press, Inc. 1976.